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# PHYSICAL MODELING TECHNIQUES FOR MISSILE AND OTHER PROTECTIVE STRUCTURES

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The following technical papers have been reviewed by our office and are approved for public release. This headquarters has no objection to their public release and authorizes publication.

1. (BMO 81-296) "Protective Vertical Shelters" by Ian Narain, A.M. ASCE, Jerry Stepheno, A.M. ASCE, and Gary Landon, A.M. ASCE.

2. (BMO 82-020) "Dynamic Cylinder Test Program" by Jerry Stephens, A.M. ASCE.

3. (AFCMD/82-018) "Blast and Shock Field Test Management" by Michael Noble.

4. (AFCMD/82-014) "A Comparison of Nuclear Simulation Techniques on Generic MX Structures" by John Betz.

5. (AFCMD/82-013) "Finite Element Dynamic Analysis of the DCT-2 Models" by Barry Bingham.

6. (AFCMD/82-017) "MX Basing Development Derived From H. E. Testing" by Donald Cole.

7. (BMO 82-017) "Testing of Reduced-Scale Concrete MX-Shelters-Experimental Program" by J. I. Daniel and D. M. Schultz.

8. (BMO 82-017) "Testing of Reduced-Scale Concrete MX-Shelters-Specimen Construction" by A. T. Ciolko.

9. (BMO 82-017) "Testing of Reduced-Scale Concrete MX-Shelters-Instrumentation and Load Control" by N. W. Hanson and J. T. Julien.

10. (BMO 82-003) "Laboratory Investigation of Expansion, Venting, and Shock Attenuation in the MX Trench" by J. K. Gran, J. R. Bruce, and J. D. Colton.

11. (BMO 82-003) "Small-Scale Tests of MX Vertical Shelter Structures" by J. K. Gran, J. R. Bruce, and J. D. Colton.

12. (BMO 82-001) "Determination of Soil Properties Through Ground Motion Analysis" by John Frye and Norman Lipner.

13. (BMO 82-062) "Instrumentation for Protective Structures Testing" by Joe Quintana.

14. (BMO 82-105) "1/5 Size VHS Series Blast and Shock Simulations" by Michael Noble.

15. (BMO 82-126) "The Use of Physical Models in Development of the MX Protective Shelter" by Eugene Sevin.

*16. REJECTED: (BMO 82-029) "Survey of Experimental Work on the Dynamic Behavior of Concrete Structures in the USSR" by Leonid Millstein and Gajanen Sabnis.

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# TESTING OF REDUCED-SCALE CONCRETE MX-SHELTERS

## EXPERIMENTAL PROGRAM

KEY WORDS: Concrete, Deformations; Loads (axial); Missile; Models; Nuclear Attack; Pressure (surface); Reinforced concrete; Shelter; Strains; Structural engineering; Tests

ABSTRACT: An experimental program involving construction and testing or reduced-scale concrete horizontal MX-Missile Shelters was conducted. The program consisted of 43 shelter specimens tested under static loading conditions. Applied loads modeled forces that might occur on the shelters from a nearby nuclear weapon attack. Loads consisted of various combinations of non-uniform radial surface pressure and axial thrust. Loads, deformations, and reinforcement strains were measured. Strength and ductility of specimens were determined. Test results were used to analyze shelter behavior under "known" loading conditions and to assist in selection of feasible shelter candidates for design.

BMO 92-017

# TESTING OF REDUCED-SCALE CONCRETE MX-SHELTERS

## EXPERIMENTAL PROGRAM

by

J. I. Daniel and D. M. Schultz,* M.ASCE

## INTRODUCTION

An experimental program involving construction and testing of reduced-scale concrete horizontal MX-Shelters was conducted by Construction Technology Laboratories, a Division of the Portland Cement Association. The program included 43 specimens tested under static loading conditions. Each specimen represented a "candidate design" being considered for prototype construction.

One deployment concept involved MX missiles stored in underground horizontal shelters. One purpose of the shelter was to protect the missile from a nearby nuclear weapon attack such that the missile could be successfully launched after an attack. In the testing program, loads modeling various combinations of forces that might occur from an attack were applied to the specimens. Loads consisted of axial thrust and non-uniform radial surface pressure. Data obtained from the test program were used to analyze shelter behavior under "known" loading conditions.

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This is the first of three papers describing the test program. Other papers describe Specimen Construction [1] and Instrumentation and Load Control.[2]

## OBJECTIVES AND SCOPE

The primary objective of the experimental program was to determine strength and ductility of plain and reinforced concrete specimens.

The objective of this investigation was accomplished within the following scope:

1. Loading techniques were developed to model design forces on reduced-scale shelters.
2. Test fixtures were designed and constructed for the simultaneous application of axial compression and non-uniform radial surface pressure on the specimens.
3. Forty-three static load tests were performed.

Final results included a set of data plots for each specimen. These data together with specific test notes, crack mapping, and pictures of tested specimens assisted in the selection of feasible candidates for shelter design.

## TEST SPECIMENS

All specimens had a 2-ft (0.61 m) inside diameter with either plain or reinforced concrete walls 1.8 (46 mm) or 2.4-in. (61 mm) thick. As shown in Fig. 1, specimen test length was 4 ft (1.22 m) with an additional 1 ft (0.30 m) at each end for load transfer. Overall specimen length was 6 ft (1.83 m). At

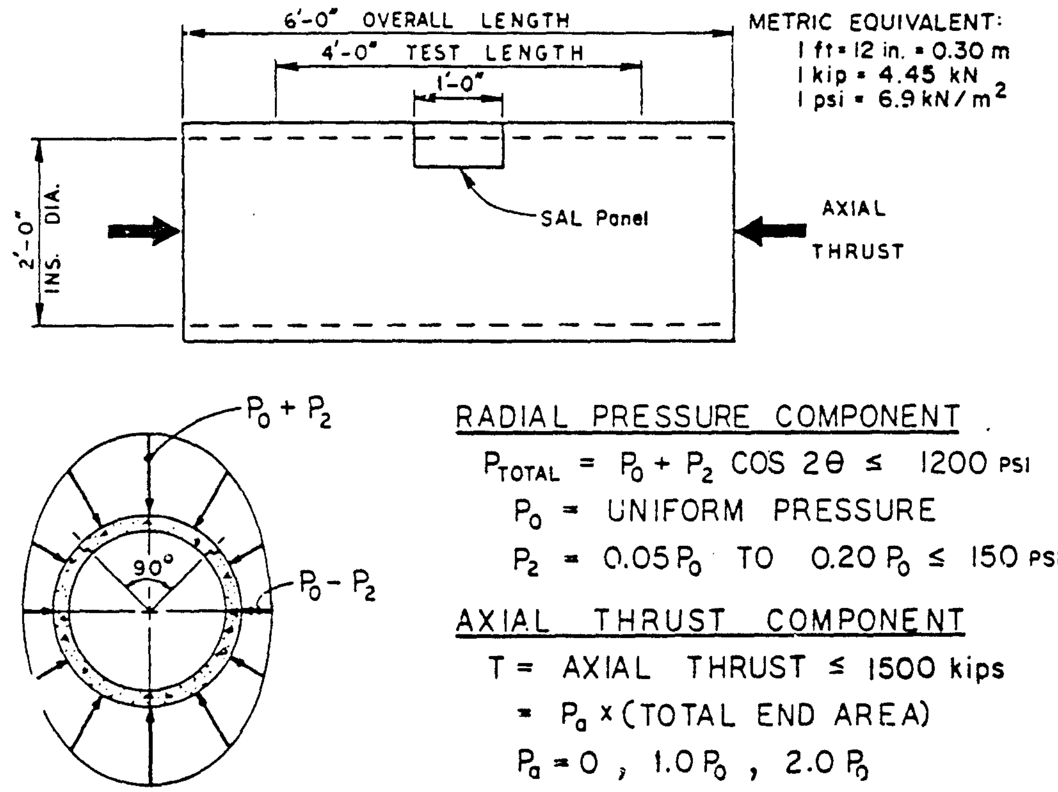


Fig. 1 Schematic of Test Specimen and Prototype Loading

specimen mid-length, there was a $90^{\circ}$ wide segment 1-ft (0.30 m) long that represented the MX-Shelter Strategic Arms Limitation (SAL) panel. This panel was fitted into the specimen with "Z" shaped joints.

Early concepts for shelter design required breakout joints (weakened plane joints) located at $\pm 45^{\circ}$ from the specimen crown on both sides of the SAL panel. Breakout joints were required in Phase 1 specimens only.

There were seven "basic" wall design configurations comprising a total of 16 wall designs. Basic design configurations were classified as follows:

A1 - plain concrete, no SAL panel

A2 - double layer reinforcement, no SAL panel

A3 - plain concrete, with SAL panel

B1 - double layer reinforcement, with SAL panel

B2 - single layer reinforcement, with SAL panel

C1 - steel liner with stud anchors, plain concrete, with SAL panel

C1 - steel liner with stud anchors, single layer reinforcement, with SAL panel

Additional variables within the basic design configurations included wall thickness, amount of reinforcement, breakout joint details, thickness of liner, spacing of studs, and gap between inner and outer Z-insert. Variable matrix and quantities included in the program are given in Table 1.

TABLE 1 - MX-HORIZONTAL SHELTERS SPECIMEN DESCRIPTION

| Construction Phase | Specimen Identification Number | Reinforcing | Liner, Studs | SAL Gap (in.) | Breakout Joint | Thickness (in.) | Total Quantity |
|---|---|---|---|---|---|---|---|
| I | A1 | None | None | No SAL | Yes | 1.8 | 2 |
| | A2 | 2 layer, 1/2% ewef | None | No SAL | Yes | 1.8 | 3 |
| | A3 | None | None | 0.025 | Yes | 1.8 | 3 |
| | B1 | 2 layer, 1/2% ewef | None | 0.025 | Yes | 1.8 | 6 |
| | B2 | 1 layer, 1% ew | None | 0.025 | Yes | 1.8 | 3 |
| | C1 | None | 16 Ga, 3-1/2 in. oc | 0.025 | Yes | 1.8 | 6 |
| | C2 | 1 layer, 1/3% ew | 16 Ga, 3-1/2 in. oc | 0.025 | Yes | 1.8 | 3 |
| II | B1.2 | 2 layer, 1/4% ewef | None | 0.025 | No | 1.8 | 2 |
| | B1.3 | 2 layer, 1% ewef | None | 0.025 | No | 1.8 | 2 |
| | C1.2 | None | 20 Ga, 4 in. oc | 0.025 | No | 1.8 | 2 |
| | C1.3 | None | 16 Ga, 4 in. oc | 0.025 | No | 1.8 | 2 |
| | C1.4 | None | 16 Ga, 3 in. oc | 0.025 | No | 1.8 | 2 |
| III | C2.2 | 1 layer, 1/3% ew | 20 Ga, 3 in. oc | 0.025 | No | 1.8 | 1 |
| | C2.3 | 1 layer, 1/3% ew | 20 Ga, 3 in. oc | 0.025 | No | 2.4 | 4 |
| | C2.4 | 1 layer, 1/3% ew | 20 Ga, 3 in. oc | 0.05 | No | 2.4 | 1 |
| | C2.5 | 1 layer, 1/3% ew | 20 Ga, 3 in. oc | 0.10 | No | 2.4 | 1 |

Notes:
ew = each way
ewef = each way, each face
Ga = gage
oc = on center

Metric Equivalent:
1 in. = 25.4 mm

## TEST LOAD REQUIREMENTS

Specimens were subjected to static loads consisting of axial thrust and non-uniform radial surface pressures that represented pressures defined in Fig. 1. Applied radial pressure modeled a distribution around the specimen circumference equal to $P_o$ + $P_2 \cos 2\theta$, where $P_o$ was a uniform pressure and $P_2$ ranged from 0.05 $P_o$ to 0.20 $P_o$. Axial thrust pressure, $P_a$, was applied as a multiple of the uniform radial pressure; i.e., 0.0 $P_o$, 1.0 $P_o$, 2.0 $P_o$, and uniaxial load only. In general, axial thrust was applied with an initial eccentricity of zero on the specimen end.

Sixteen different combinations of $P_a/P_o$ were used in the testing program. A description of each loading condition is given in Table 2.

All specimens were to be tested to failure or to the limits of the test equipment.

## DESCRIPTION OF TESTING APPARATUS

The test apparatus was designed to apply any one of the following loadings:

1. Axial load only
2. Axial load with radial surface pressure
3. Radial surface pressure only

### Radial Surface Pressure Loading

Radial pressure was applied to the specimen by pressure bladders housed between the specimen and a steel pressure

TABLE 2 - LOADING CONFIGURATIONS

| Type | Description | $P_a/P_o$ | $P_2/P_o$ |
|---|---|---|---|
| A | Uniform Radial Only | 0 | 0 |
| B | Nonuniform Radial Only | 0 | 0.05 |
| C | Nonuniform Radial Only | 0 | 0.10 |
| D | Axial and Nonuniform Radial | 1.0 | 0.05 |
| E | Axial and Nonuniform Radial | 1.0 | 0.10 |
| F | Axial Only | $\infty$ | - |
| G | Axial and Nonuniform Radial | 2.0 | 0.05 |
| H | Axial and Nonuniform Radial | 2.0 | 0.10 |
| I | Axial and Nonuniform Radial | 1.0 | 0.15 |
| J | Axial and Nonuniform Radial | 2.0 | 0.15 |
| K | Nonuniform Radial Only | 0 | 0.15 |
| L | Nonuniform Radial Only | 0 | 0.20 |
| M | Nonuniform Radial Only | 0 | $P_2 - P_o = 25$ psi |
| N | Nonuniform Radial Only | 0 | $P_2 - P_o = 50$ psi |
| P | Axial and Nonuniform Radial | 1.0 | 0.20 |
| Q | Axial and Nonuniform Radial | 2.0 | 0.20 |

Metric Equivalent:
1 psi = 6.9 kPa

vessel. The pressure vessel is shown schematically in Figs. 2 and 3.

Bending in the pressure vessel due to non-uniform radial pressure was resisted by steel ribs around the circumference of the 1-1/2-in. (38 mm) thick steel vessel wall.

The pressure vessel could resist the combined effects of $P_o$ and $P_2$ equal to 1050 psi (7.2 MPa) and 150 psi (1.0 MPa), respectively. In addition, it could accommodate $\pm$ 4 in. (102 mm) of diameter change under non-uniform radial pressure. Vessel weight of 15,000 lb (6800 kg) was supported on its own legs and not by the specimen prior to or during the test.

The radial pressure component indicated in Fig. 1 was modeled using three distinct pressures applied by eight specially made neoprene bladders housed between the specimen and steel vessel. Pressure bladders labeled A in Fig. 2 applied the largest pressure. Pressure bladders labeled B applied the smallest pressure. Pressure bladders labeled C applied the middle pressure. Segments A and B were $60^{\circ}$ wide and Segments C were $30^{\circ}$ wide. Bladders were partially separated by steel partitions to limit force transfer between adjacent bladders.

To develop the model pressure loading, a computer program was written to determine the effects of several pressure configurations around the circumference of the specimen. The model that was finally selected closely approximated the moments, shears, and thrusts, induced from the prototype loading

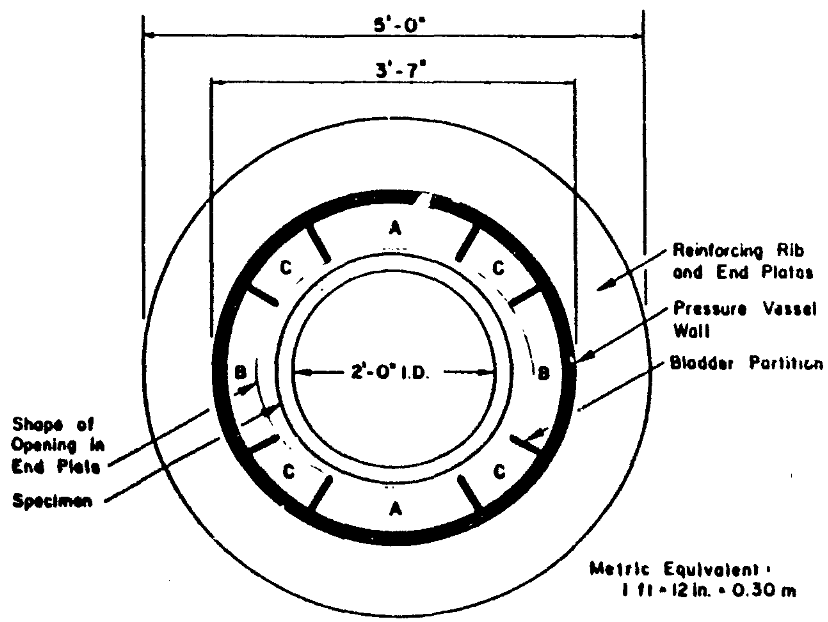


Fig. 2 Cross-Section of Pressure Vessel (Plan)

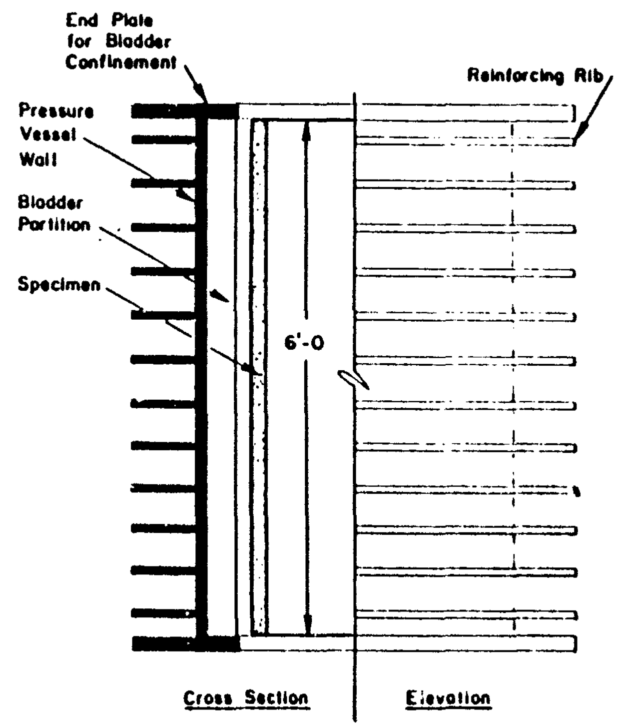


Fig. 3 Cross-Section and Elevation of Pressure Vessel

distribution shown in Fig. 1. Plots of moment, shear, and thrust occurring on the specimen due to both the prototype component and modeled pressure component are shown in Fig. 4. As indicated, model load application provided nearly identical moments, shears, and thrusts at all locations where maximum and minimum values occurred. This included shear at the $45^{o}$ line in the specimen.

## Uniaxial Compressive Loading

Arrangement of the testing apparatus for uniaxial compressive loading is shown in Figs. 5 and 6. Also indicated in these figures is the position of the radial pressure vessel. Test specimens were positioned with their longitudinal axis in a vertical direction.

The axial test fixture was constructed of prestressed concrete to minimize stored energy. Reduction of stored energy in the system during testing facilitated recording of inelastic specimen behavior. The reaction frame was capable of resisting 1500 kips (6670 kN) of axial force. Axial load was applied by a 3500-kip (15,570 kN) hydraulic ram acquired on loan from National Aeronautics and Space Administration.

As shown in Fig. 6, bearing plates transferred axial load from ram to specimen and from specimen to laboratory floor. Bearing plates were constructed of reinforced concrete and steel plates. The shape of each bearing plate conformed to the opening in the end plate of the pressure vessel. There was a 1/16-in. (1.6 mm) gap between the bearing plate sides and the

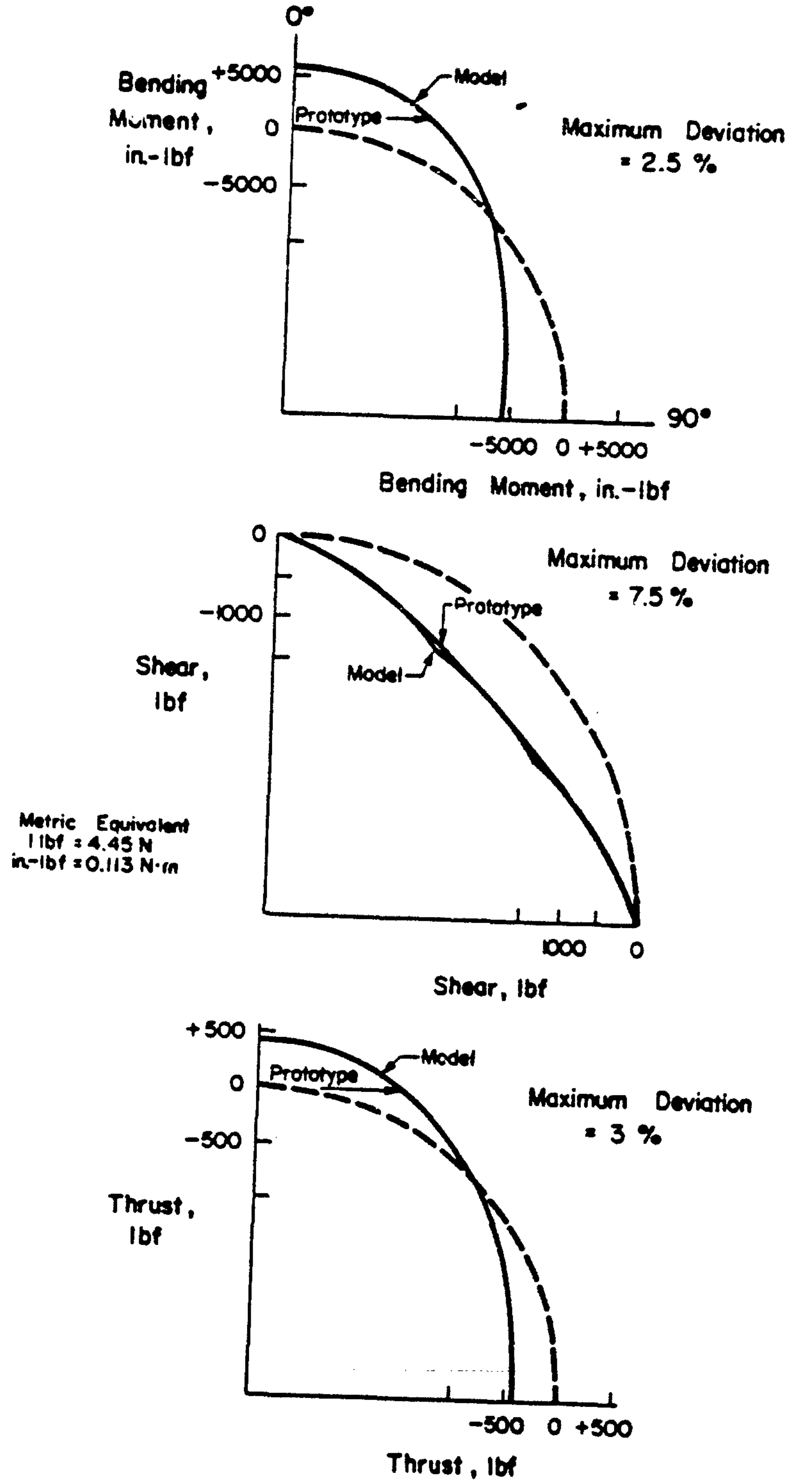


Fig. 4 Plots of Bending Moment, Shear, and Thrust for Prototype and Model Load Application

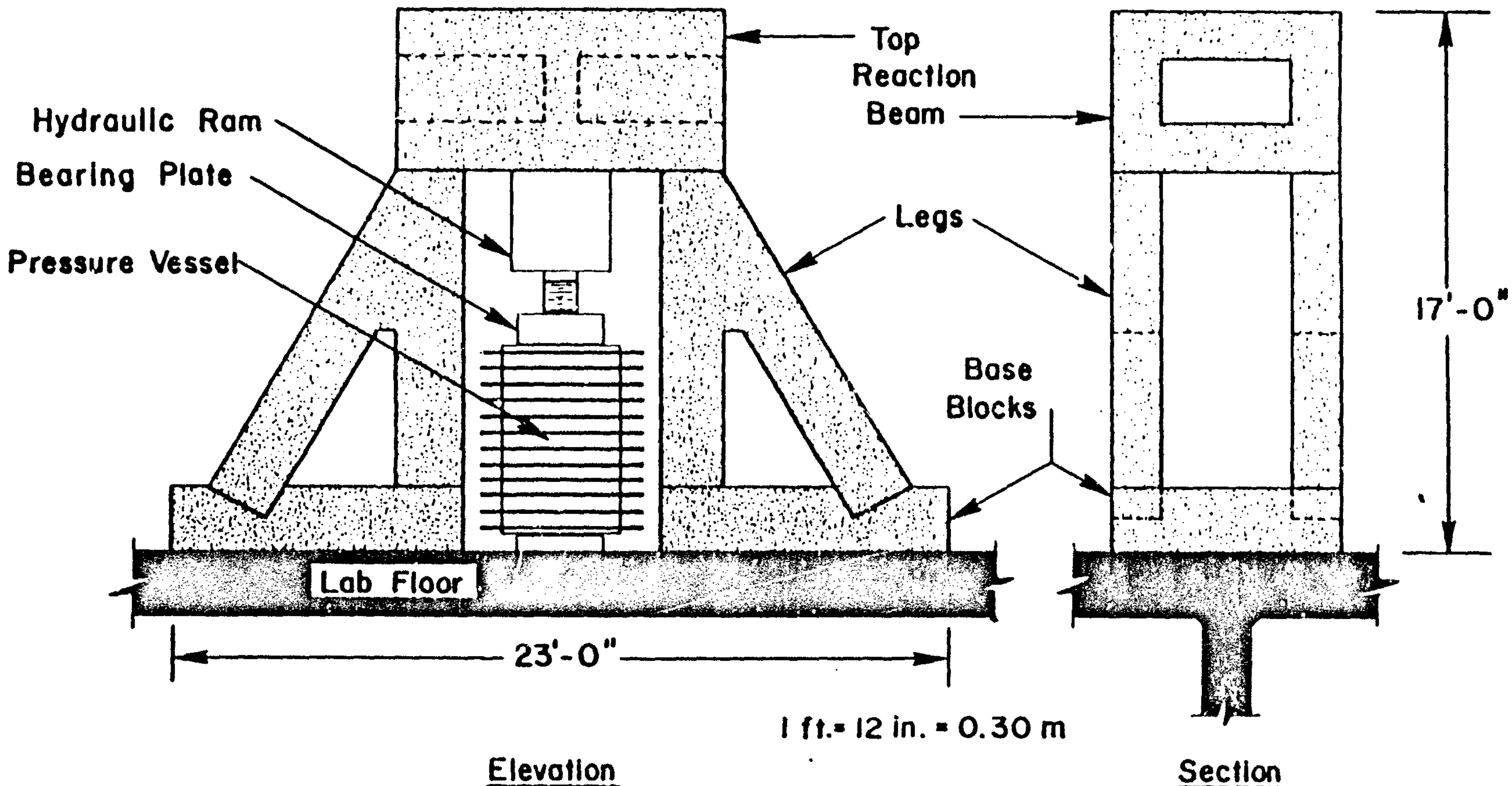


Fig. 5 Axial Reaction Frame

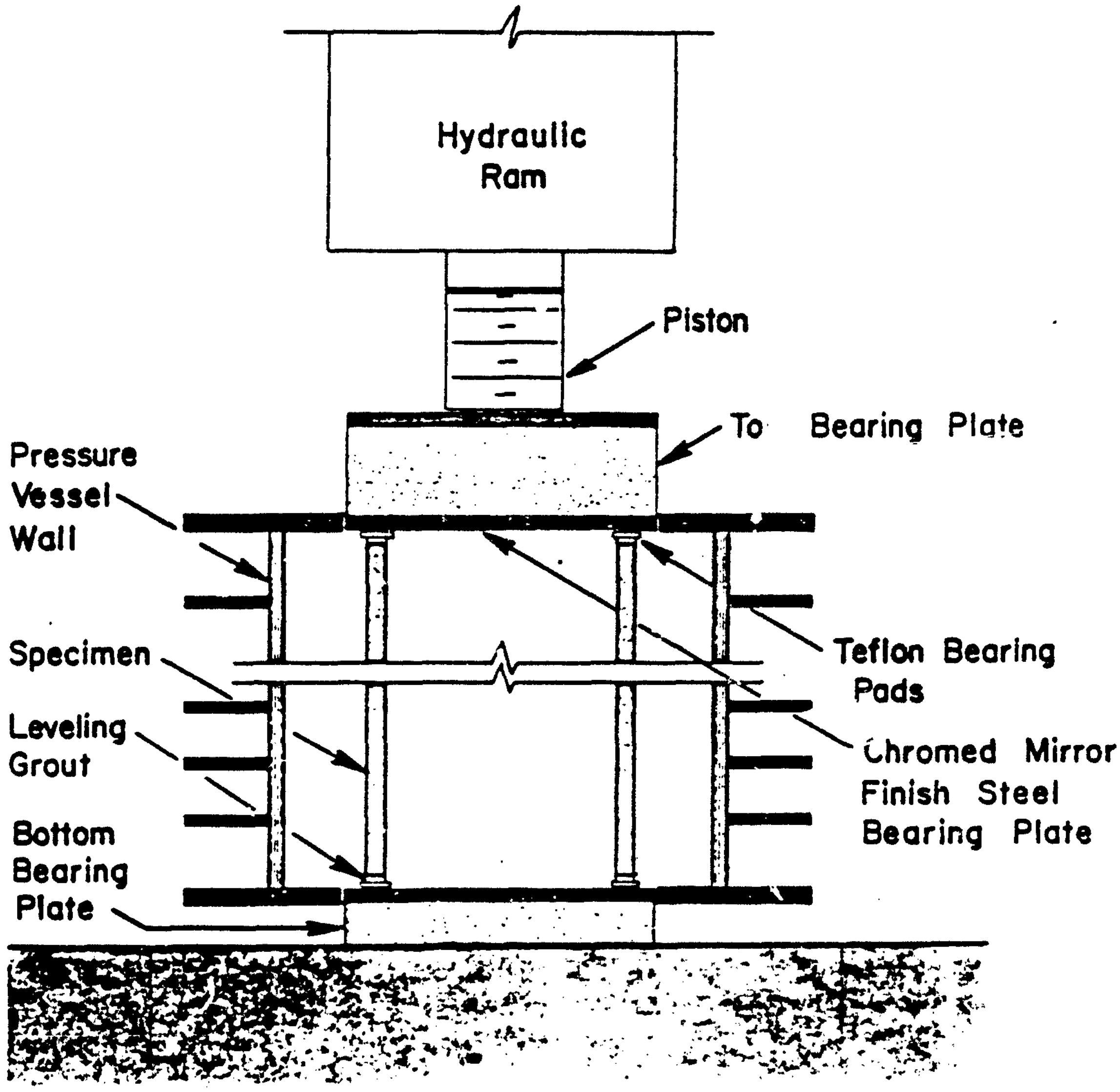


Fig. 6 Cross-Section of Axial and Radial Load Application System

end plates sides of the pressure vessel. This "fit" assured continuous alignment of the pressure vessel during each test. The combination of bearing plate and end plate also assured complete and continuous confinement for the enclosed pressure bladders described earlier.

The steel bearing plates were level and flat with a mirror-finish chrome plating. Teflon bearing pads, shown in Fig. 6, were placed on the grout capped ends of each specimen. The combination of Teflon on chrome gave a coefficient of friction of about 0.04. Low friction allowed the specimen to deform radially under combined axial and radial load while inducing minimum bending stresses into the specimen wall. Capping specimen ends with grout facilitated leveling of specimen ends, thus ensuring initial uniform axial load application.

A photograph of the test setup is shown in Fig. 7.

## Calibration

Calibration of radial pressure and axial load was performed using a specially built calibration rig shown in Fig. 8. This calibration rig was a solid reinforced concrete cylinder, identical in size to a test specimen. Inside the calibration rig were six 100-kip (445 kN) load cells housed behind a 48.0 x 7.2-in. (1220 x 180 mm) piston.

The calibration rig was inserted into the pressure vessel and the upper bearing plate was lowered to contact its top. The bladders were then pressurized while loads applied into the piston and into the top bearing plate were being recorded.

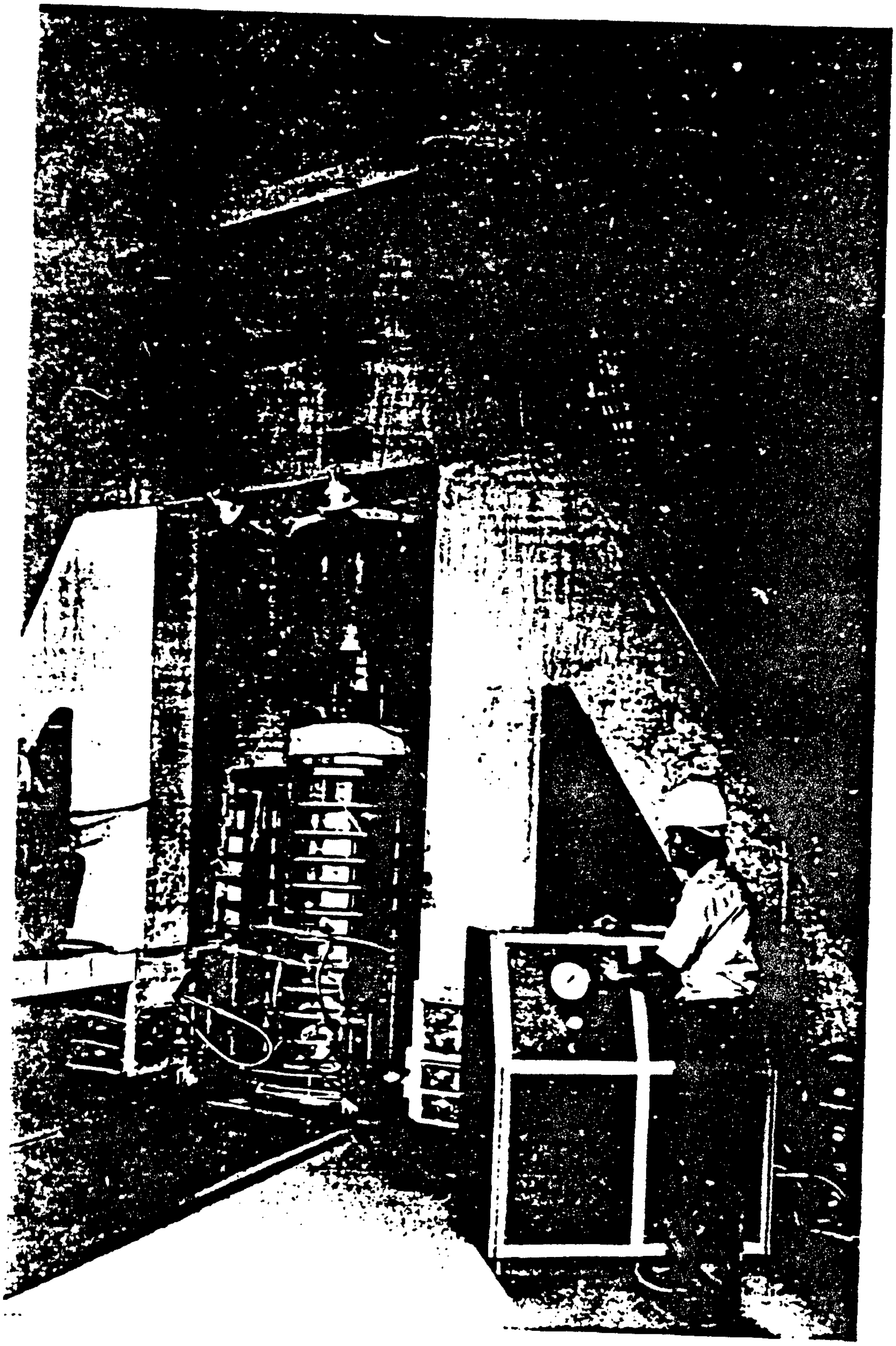

Fig. 7 Photograph of Test Setup

Calibration factors used to correct applied load or pressure were determined using the recorded calibration loads and known contact areas. These factors were directly programmed into the computer to automatically correct subsequent test data.

## TEST PROCEDURE

Preparation and testing of one specimen took approximately four hours.

### Specimen Preparation

Prior to testing, each specimen was checked against construction specifications.[1] Steps in specimen preparation were as follows:

1. Exterior instrumentation[2] was connected to the inside wall of the specimen.
2. Specimen bottom was leveled with a quick setting grout using a specially built leveling platform. This procedure was similar to capping a 6 x 12-in. (152 x 305 mm) concrete cylinder.
3. Instrumentation was plugged into the data acquisition system and checked for proper functioning prior to inserting specimen into the pressure vessel.
4. All visible cracks in a specimen prior to testing were recorded.
5. Specimen was inserted into the pressure vessel.
6. Specimen/vessel combination was rolled on rails into the axial test fixture.

7. Instrumentation was plugged in and cables were taken out through an opening in the top bearing plate. Teflon pads were placed under the specimen.
8. Pressure vessel was lowered into the proper position.
9. Quick setting grout was placed on the specimen top. The level top bearing plate was lowered to contact and squeeze enough grout out to ensure a level specimen top. Grout was allowed to dry.
10. Top bearing plate was raised to permit placement of the top Teflon bearing pads. Top bearing plate was lowered again.
11. Pressure bladders were filled with oil. All air was bled from the bladders.
12. Test was ready to begin.

## Test Conduct

Each test was fully computerized. The responsibility of the testing engineers was to monitor test progress, make any necessary manual adjustments, and take test notes. Technicians were posted around the test fixture only to note the occurrence of anything out of the ordinary.

Prior to the start of each test, the proper loading functions were programmed into the computer controlled loading system. A detailed description of the load control system is given in Ref. 2. During the test, an entire set of data was collected by the data acquisition system approximately every 10 seconds. In this time, the computer was programmed to accept and store

raw data. In addition, there was ample time to reduce and display necessary data for observation of test progress. This "Test Control" information was continuously displayed on a video screen (CRT) and updated every 10 seconds. A spontaneous user request provided a hardcopy of the data. Control information consisted of the following items:

1. Axial Load
2. Three Radial Pressures
3. Axial Shortening
4. Radial Deformation
5. All Strain Gage Data

In addition to control data displayed on the CRT, continuous plots were recorded on X-Y plotters. Detailed description of the data acquisition system, instrumentation, and data handling are given in Ref. 2.

A test was terminated under any of the following conditions:

1. Design axial load or radial pressure limits were reached
2. Specimen failed catastrophically
3. Axial load or radial pressures dropped to 50% of peak values
4. Allowable specimen deformation, i.e., 4-in. (102 mm) was exceeded

## Post-Test Examination

Observed failure mode of each specimen was recorded. Photographs were taken and pre- and post-test crack patterns were plotted.

## TEST RESULTS

Approximately 24 hours after each test, the client was provided with the following test results:

1. Test notes
2. Reduced data recorded on magnetic tape
3. Data plots
4. Map of crack patterns

Photographs were provided to the client on a weekly basis. Tested specimens are shown in Fig. 9. Examples of data plots are presented in Ref. 2.

## SUMMARY

The fast-paced test program was successfully completed within 11 months, from November 1979 to October 1980. In this time the following was accomplished:

1. Design and construction of test fixtures
2. Calibration of test fixtures
3. Design and setup of load control and instrumentation systems[2]
4. Design and fabrication of specimen forms for casting[1]
5. Casting and instrumenting 43 test specimens[1]
6. Testing 43 specimens

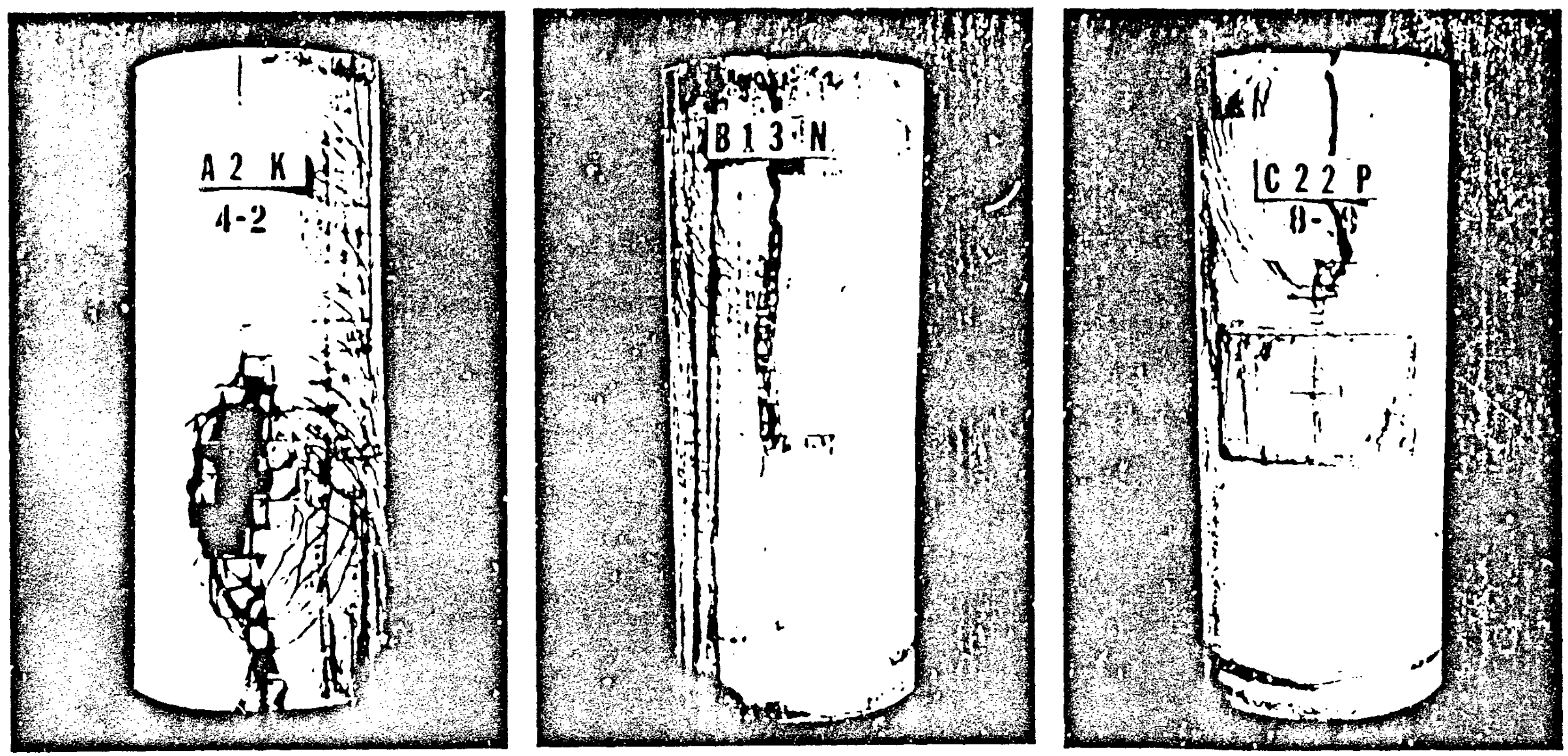


Fig. 9 Specimens After Testing

Test results were used to analyze shelter behavior under "known" loading conditions and to assist in the selection of feasible candidates for shelter design.

## ACKNOWLEDGMENTS

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2. Hanson, N.W. and Julien, J.T., "Testing of Reduced-Scale Concrete MX-Shelters - Instrumentation and Load Control," Paper submitted to ASCE Committee on Experimental Analysis and Instrumentation, January 1982.